

SANTA CLARA UNIVERSITY
Department of Mechanical Engineering
Santa Clara, CA 95053

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Attn: Dr. B. Sridhar, MS 210-9

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Prepared by:

Professor P.K. Menon
Research Professor

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1. Introduction

Early research on the development of machine vision algorithms to serve as pilot aids in aircraft flight operations is discussed. The research is useful for synthesizing new cockpit instrumentation that can enhance flight safety and efficiency. With the present work as the basis, future research will produce low-cost instrument by integrating a conventional TV camera together with off-the-shelf digitizing hardware for flight test verification. Initial focus of the research will be on developing pilot aids for clear-night operations. Latter part of the research will examine synthetic vision issues for poor visibility flight operations. Both research efforts will contribute towards the high-speed civil transport aircraft program.

It is anticipated that the research reported here will also produce pilot aids for conducting helicopter flight operations during emergency search and rescue. The primary emphasis of the present research effort is on near-term, flight demonstrable technologies. The following sections will discuss each of the research items in further detail.

2. Pilot Aids for Night Landing and Takeoff

Various difficulties experienced by the pilots while executing night landing and takeoff operations are well documented [1]. Altimeter, Pitot sensor, Gyrocompass, attitude indicator, and a radio are sufficient to aid the pilot in aircraft control and navigation during cruise flight at night. However, these instruments are not useful for night time landing, even under good visibility conditions. Pilots have to depend on runway lights to provide the appropriate landing-takeoff cues.

Reference 1 documents the several dangerous optical illusions that can arise during nighttime landing operations. Most of these arise due to the absence of scene shading, which often makes it difficult to perceive the depth of the visual field. Consequently, most pilots are uncomfortable landing at an unfamiliar airfield at night. Night operational problems include difficulty in judging the range, altitude, attitude and runway limits when observed from the air.

Additional difficulties arise due to the complex approach procedures required at many airports. Airports near population centers often have flight hazards such as tall buildings and transmission towers. Restrictions arising from noise abatement regulations can further contribute towards operational difficulties. Typically, aircraft are required to employ a steeper approach path before capturing the glide slope towards the runway. At night, this means that the pilot must be able to accurately judge the distance to the airport throughout the landing and takeoff phases. Operating under such conditions is a high-stress activity for the pilot because any deviation from the prescribed procedure can have disastrous consequences.

Advanced guidance systems such as the microwave landing system (MLS) can obviate these difficulties. However, such systems are expensive and are not likely to find widespread application in smaller airports. Guidance methods that do not need expensive antennas and

transmitters are likely find higher levels of acceptance from the aviation community. Thus, runway lighting systems will continue to be the chief landing aids for night flying. Federal Aviation Administration has recognized this fact, and is investing in the deployment of various visual landing aids. Recently deployed PAPI system [2] is an example of this initiative.

The objective of the present research is to further increase the utility of the existing runway lighting systems through the use of an on-board machine vision system. Machine vision systems have shown excellent promise in the development of rotorcraft nap-of-the-earth flight navigation systems [3, 4]. The main characteristic of such systems is their ability to generate position of various objects within the field-of-view with *respect to the vehicle* using an image sequence. Conversely, they can be used to determine the position of a flight vehicle with respect to specific objects within the field-of-view. The problem considered in this proposal is considerably simpler than those in References 3 and 4, because the runway lighting system has a well defined structure.

One of the objectives of the present research is to develop an automatic machine-vision based system that will use the image sequence from an aircraft mounted camera to compute down-range, cross-range, altitude, and glide slope. These data can be displayed to the pilot in a suitable form. Pilot display may include range to go, desired Vs actual glide slope, cross range error with respect to the runway centerline etc. In other words, the present research attempts to develop a vision-based equivalent of a microwave landing system (MLS).

Algorithms will be synthesized to determine the aircraft position, attitude, and velocity vectors with respect to an airport equipped with a standard runway lighting system. An off-the-shelf medium to low resolution TV camera together with a low-cost digitizer will be used to collect images of the airport. These images will form the input to the machine vision algorithm implemented on a personal computer. The computer outputs will be displayed to the pilot in the form of a guidance display.

The vision system will also find extensive use in helicopter flight operations. Specifically, the system can be used to aid the pilot to precisely align and determine the distance to the landing area. Note that helicopter pilots have difficulty in seeing the landing area when they are close to the ground. This can be hazardous when the helicopters are trying to land in relatively unfamiliar and unprepared surface. A methodology to aid helicopter pilots in such situations will be developed as a part of future research.

We expect a machine vision-based instrument to provide accurate navigational information to the pilot. Initial studies indicate that such an instrument can be very accurate. Two distinct approaches have been explored to date. In the first approach, aircraft altimeter data is used to determine the down-range and cross range locations of various runway lights. These computations require the knowledge of camera/aircraft attitude with respect to the runway. When implemented, this algorithm can be yield the aircraft glide slope, and the aircraft heading angle orientation with

respect to the runway. The second approach attempts to compute the aircraft position with respect to the runway without using the altimeter data. The computational method in this case turns out to be iterative. The well known Newton-Raphson method proved to be very effective for this problem. However, the procedure still requires the aircraft attitude data. We believe that the computational procedure can be refined to a point where it would be possible to obtain all the runway related aircraft state variables for pilot display and guidance.

Results from this research are being written-up as a paper for the 1994 AIAA Guidance, Navigation, and Control Conference.

2.1. Future Research on Pilot Aids for Night Landing and Takeoff

With the foregoing, the following research directions are proposed for the next three year period:

1. Develop the vision-based aircraft position determination method using all the available information about the runway lighting system.
2. Investigate methods for vision-based aircraft formation keeping, rendezvous, and avoidance.
3. Develop a pilot assisted guidance scheme to enable the optimum use of the navigation data.
4. Demonstrate the performance of the algorithm using a scene simulation on a 3-D Graphics computer.
5. Configure a flight test system using off-the-shelf video and computing hardware.

Periodic presentations, oral and written reports will be provided at the end of each research period.

3. Synthetic Vision as an Aid to Low Visibility Landing

Development of synthetic vision aids is considered to be the next step in improving airline operational efficiency [5 - 7]. Although microwave landing systems are the state-of-the-art for extremely low visibility operations, these systems require significant investment both on the ground and on each aircraft. Secondly, although these guidance systems are effective in helping aircraft land, they are not useful in ground operations such as taxi, and terminal approach. This fact forces the airport to operate at significantly reduced capacity. This forms one of the motivating factors for the development of a synthetic vision system. Another motivating factor is the recent research initiative on high-speed civil transport program. Due to their relatively inefficient low speed performance, fixed-configuration supersonic aircraft have to maintain a high angle of attack during approach and landing. Since these aircraft configurations have long nose sections, this implies that the pilots will be unable to see the ground during landing. Aircraft such as the Anglo-French *Concord* employ an articulated nose section to improve pilot visibility. However, recent studies show that avoiding drooped-nose configuration could save between 1500 and 2000 pounds of structure weight, and reduce gross takeoff weight as much as 10,000 pounds. Synthetic vision can be used to avoid the use of the articulated nose section, thereby increasing the system

efficiency. Finally, if a synthetic vision system permits reduced-visibility weather conditions, the aircraft could carry less reserve fuel for diversion purposes. Less fuel leads to smaller size aircraft, which can further reduce the airframe weight when compared with cargo/passenger load.

Synthetic vision concept currently under development at various aeronautical research centers focus on generating out-of-the-window scene by combining information from various sensors. For instance, images obtained from low-light level TV cameras can be combined with those obtained using infrared cameras, and passive millimeter wave radar to generate an integrated display system. The image displayed to the pilot may include various levels of detail. At a very basic level, a wire frame model of the airport and the surrounding area may be displayed to the pilot. More advanced systems can generate and display fully shaded color images of the scene.

The fundamental principle that aids in generating synthetic vision displays is the fact that the scene geometry forms unifying basis for all the images. Geometric data of most major airports are currently available as computer data bases used in training simulators. The challenge is in synthesizing algorithms that can combine this data with those from other sensors to form a display system that can augment pilot effectiveness.

Initial research into such algorithms is given in Appendix - A. That research will demonstrate the fusion of geometric data with a gray scale image. The method is based on the classical predictor-corrector paradigm. The geometry data together with an initial image are used to form a predicted image. Whenever the actual image is obtained, the error between the predicted and actual images are used to update the initial image. The updating process can include replacing areas of the actual image by stored texture maps corrected for illumination conditions. The assumption in such an approach is that the geometric data is accurate, while the actual images contain various errors due to imaging sensor characteristics.

The material presented in Appendix-A illustrates the development of an image predictor that combines an image with the corresponding geometric data to form a new image. Measured image can be combined with the predicted image to form an improved image. The subsystem for performing image correction is currently under development. As an initial application of the predictor-corrector paradigm, Appendix - A discusses an image-based ranging scheme for ANOE flight.

3.1. Future Research on Synthetic Vision

In view of the early research results using the predictor-corrector paradigm, the following research directions are proposed for the next research phase.

1. Investigate alternate methods for image prediction.
2. Formulate a corrector scheme for updating the image.
3. Generate corrupted images by superimposing random patches of textures on laboratory image sequences. Generate simulated images for Passive millimeter wave radar and Infrared sensors.

4. Using these images, demonstrate the performance of the predictor-corrector method for synthetic image generation.

Progress on these and other related research items will be reported using periodic presentations and reports.

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Appendix-A : Progress in Combining Geometric Data with an Image

Abstract

Synthetic Vision systems are considered to be a crucial element in the operation of next generation transport aircraft. This appendix reports on the progress in combining known geometric data with an image sequence of the scene. Proposed procedure employs the predictor-corrector paradigm. As an application, the use of the proposed method for developing a field-based ranging algorithm is also discussed. Convergence properties are examined using a simplified analysis.

Introduction

Two approaches have been advanced for guiding next generation aircraft under Category III flight conditions. First of these is the Microwave Landing System (MLS). Synthetic vision forms the second approach. In the first approach a microwave beacon is used to guide the aircraft to the touch-down point, and in initiating the flare maneuver. It does not aid the aircraft taxi, or maneuver in the terminal area. The system operates in a heads-down mode, with the pilot using the flight director display to operate the aircraft. These systems have been around for a number of years, and are considered reliable.

Synthetic vision approaches, on the other hand, focus on a heads-up mode by displaying a synthetically generated imagery to the pilot. The imagery is generated by combining computer data base with the data obtained from several sensors, most of which operate in a passive fashion. Typical sensors include passive millimeter wave radar, low-light TV, and infrared imaging systems.

While most of the MLS equipment is on the ground, with the aircraft carrying only a receiver, synthetic vision approach is an aircraft based solution. All the equipment for the synthetic vision will be carried on-board the aircraft, including the computer data bases.

The major challenge for synthetic vision is in developing computer algorithms that can accept data from disparate sources and generate an intuitively obvious visual display for pilot's use. Computer data bases generally contain three-dimensional data about various features on the airfield under consideration. Various sensors produce segments of the field-of-view, which have to be combined together to form an image that the pilot can use to land the aircraft. Visual data from these sensors generally do not have sufficient resolution or detail to be directly useful to the pilot.

This appendix discusses early research experiments on synthetic vision. The predictor-corrector paradigm forms the basis for the system. An image predictor and one of its applications will be discussed in the following sections. Corrector algorithms are currently under development.

Image Predictor

Image predictor uses an image and the associated geometric data to form a new image based on the camera movement. The image predictor takes an image specified as a two-dimensional array $E(i, j)$, together with a depth array $Z(i, j)$ and vehicle/camera motion parameters to come up with a predicted image $E_p(i, j)$. Only certain parts of the images can be predicted because of the limitations

in the camera field of view. Regions where it is not feasible to predict, segments of the actual image will have to be used.

Image prediction method will depend upon the type of processing that has been carried out on the original image. This fact motivates the analysis of the imaging process. Digital images are obtained by processing continuous images through a spatio-temporal sample-and-hold operation. Gray-scale image display systems on computer normally employ uniform irradiance in a pixel, effectively implementing a zeroth-order hold. If the image sampling is carried out at a frequency satisfying the sampling theorem, continuous image can be recovered from the discrete representation using various hold functions. However, the purpose to which the resulting image is put to determines the type of hold function that should be implemented. For instance, if the objective is to zoom-in, zeroth-order hold would yield an image of lower resolution [1]. A first-order hold is a superior choice in this situation. On the other hand, if the objective is to zoom-out, zeroth-order hold will be adequate to preserve the resolution. Various steps involved in implementing an image manipulation system is shown in Figure 1.

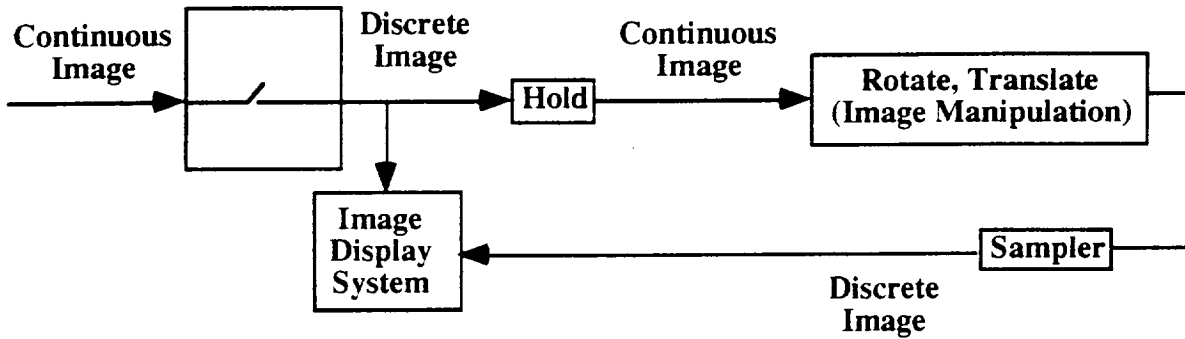


Fig. 1. Image Manipulation System

A digital camera produces a sampled image for use with various other subsystems. The image can be displayed using various hold functions. Hold function converts the digital image into a continuous form. Continuous images can be rotated and translated depending upon the camera motion. The resulting continuous image can then be re-sampled. If the original spatio-temporal sampling rate satisfies the sampling theorem [1], the manipulated image will not contain any distortion. However, the type of hold function implemented in the system can contribute to loss of resolution.

An issue that needs to be resolved before implementing an image predictor is that of the scene depth distribution. Clearly, the scene depth can vary dramatically from pixel to pixel. Depending upon the distance of the object from the camera, the scene depth could vary even within a pixel. However, since a pixel is the smallest unit of the image, it will be assumed that the scene depth is uniform over the entire pixel area. Although logically correct, this assumption can lead to

scene depth displaying jagged edges for objects that are close to the camera. If this problem is serious, the jagged edges can be eliminated only by using a camera with improved resolution.

With this background, the prediction problem may be defined as: *Given an image (Pixel array consisting of the irradiance at each pixel), camera focal length, focal plane array dimensions or the field-of-view, camera rotation and translation with respect to a pre-specified datum, and depth at each pixel, predict the next image.*

Denote a specific pixel in the image plane by $P(i, j)$. Let the row dimension of the image plane be n and the column dimension be m . Let the field-of view (in radians) along the horizontal dimension be d and that along the vertical dimension be w . Thus, the dimensions of a pixel are $(df)/n \times (wf)/m$. Assume that the image plane coordinate system is located at the center of the picture. Thus, the picture dimensions with respect to the origin are: $-(df)/2, (df)/2, -(wf)/2, (wf)/2$.

At a particular pixel $P(i, j)$, with i, j starting at the top left hand corner of the picture, perspective projection geometry can be used to relate the position coordinates of the visual field with the pixel location. Horizontal and vertical location of the four corners of the pixel with respect to the origin of the image coordinate system can be obtained as:

Top left corner : $df [(i - 1)/n - 1/2], wf [(j - 1)/m - 1/2]$

Top right corner: $df [i/n - 1/2], wf [(j - 1)/m - 1/2]$

Bottom left corner : $df [(i - 1)/n - 1/2], wf [j/m - 1/2]$

Bottom right corner : $df [i/n - 1/2], wf [j/m - 1/2]$

Pixel center : $df [(i - 1/2)/n - 1/2], wf [(j - 1/2)/m - 1/2]$

The discrete sample will be assumed to be located at the pixel center. Let $x_{i,j}, y_{i,j}, z_{i,j}$ be the inertial coordinates of an object at pixel location (i, j) . It can be shown [2] that the inertial position coordinates can be related to the camera position coordinates as:

$$\mathbf{x}_c = \mathbf{T}_1 \mathbf{T}_2 (\mathbf{x} - \mathbf{x}_v) - \mathbf{T}_1 \mathbf{l}$$

In response to the vehicle motion by $\Delta \mathbf{x}_v$ the position of objects in the camera coordinate system will change to:

$$\Delta \mathbf{x}_c = \mathbf{T}_1 \Delta \mathbf{T}_2 (\mathbf{x} - \mathbf{x}_v) - \mathbf{T}_1 \mathbf{T}_2 \mathbf{x}_v$$

$$\mathbf{x}_c + \Delta \mathbf{x}_c = \mathbf{T}_1 (\mathbf{T}_2 + \Delta \mathbf{T}_2) (\mathbf{x} - \mathbf{x}_v) - \mathbf{T}_1 \mathbf{l} - \mathbf{T}_1 \mathbf{T}_2 \mathbf{x}_v$$

If the components of the vectors $(\mathbf{x}_c + \Delta \mathbf{x}_c)$ and $\Delta \mathbf{x}_c$ are known, the pixel displacement at any pixel location x_p, y_p can be computed as:

$$\Delta x_p = f \Delta y_c / (x_c + \Delta x_c) - x_p \Delta x_c / (x_c + \Delta x_c)$$

$$\Delta y_p = f \Delta z_c / (x_c + \Delta x_c) - y_p \Delta x_c / (x_c + \Delta x_c)$$

The pixel displacement can be used to predict the image. Due to the fact that depths at each pixel are different, the new image will not be on a uniform grid. Moreover, there may be areas where the image "tears", i. e. none of the image intensities may map to a certain areas of the image. Additionally, we may have areas where the predicted image "folds", i.e. areas where several pixels would get mapped into. In the case of folding, it is clear that the pixels corresponding to objects behind the pixel under consideration can be deleted because all the objects are assumed to be opaque. Treatment of tears, however, is not direct. Although irradiance interpolation using nearby pixels appears to be an obvious approach, it is not desirable. This is because of the fact that the areas where the image "tears" correspond to occluding objects moving away from the line of sight due to camera motion. Whenever the image tears, it is better to avoid prediction and use the actual image.

To summarize, the image prediction process proceeds as follows:

1. Based on an initial knowledge of the depth map $\mathbf{x}$, and vehicle-camera motion $\mathbf{x}_v$, compute $(\mathbf{x}_c + \Delta\mathbf{x}_c)$ and $\Delta\mathbf{x}_c$. Compute the pixel displacements $\Delta x_p, \Delta y_p$ at each pixel.
2. Transform the current sampled image using the computed pixel displacements. This will yield a sampled image on a non-uniform grid. Discard pixels based on which pixel is in front of the other pixels mapped to the same location.
3. Assuming that the sampling theorem is satisfied, convert a sampled image to continuous form using a "hold" function. First-order hold will yield acceptable fidelity in most digital image sequences.
4. Sample the transformed continuous image on the original uniform grid to generate the predicted sampled image.
5. Assuming that the scene depth is constant over an individual pixel area, transform the range map also.
6. Fill-in areas of "tears" using the actual image.

Note that the prediction process does not have to be perfect for the method to work satisfactorily. The correction algorithm under development will ensure that the predicted image remains close to the actual throughout the process.

Linear Prediction

The image prediction process described in the foregoing can demand excessive computing time. If the temporal sampling rate of the imaging process is sufficiently high, the differences in images in a sequence will be small. Under this condition, it is feasible to employ a linear image prediction technique. Taylor series expansion of an image about each pixel forms the underlying principle for such a process. Taylor series expansion can be combined with perspective projection relations to form image-based ranging equation given in Reference 2. If the camera undergoes a pure translation, the image-based ranging equation will be as follows:

$$E_2 = E_1 + \left[\frac{\partial E_1}{\partial x_p} [x_p \Delta z_0 - f \Delta x_0] + \frac{\partial E_1}{\partial y_p} [y_p \Delta z_0 - f \Delta y_0] \right] \frac{1}{z - z_0 - \Delta z_0}$$

E_2 is the predicted image, E_1 is the initial image and the scene depth is z . The camera is assumed to have undergone a translational motion of $\Delta x_0, \Delta y_0, \Delta z_0$. The initial location of the camera is assumed to be x_0, y_0, z_0 . The variables x_p, y_p are the pixel location in the image plane, and f is the camera focal length.

This equation can be used to perform rapid image prediction. Due to the nature of the linear prediction process, difficulties such as tearing and folding will not arise. This is not necessarily good, since occlusion is a real phenomenon that needs to be included in the image prediction process. Thus, in order to maintain fidelity, it is important to periodically replace predicted images with actual images.

The image predictor can be combined with a correction algorithm to generate a synthetic vision system. The corrector has the responsibility for ensuring the consistency between the scene geometry and the corresponding image. Various aspects of the corrector will be pursued in the ensuing research period. The utility of the image predictor discussed in the foregoing can be illustrated using an example. In the following subsection, we will illustrate the use of the image predictor for constructing an image-based ranging scheme.

A Predictor-Corrector Algorithm for Image-Based Ranging

The development will employ the vision-based ranging equation developed in Reference 2. The ranging equation from Reference 2 is:

$$E_2 = E_1 + \left[\frac{\partial E_1}{\partial x_p} [x_p \Delta z_0 - f \Delta x_0] + \frac{\partial E_1}{\partial y_p} [y_p \Delta z_0 - f \Delta y_0] \right] \frac{1}{z - z_0 - \Delta z_0}$$

In this equation, E_1 is the first image, E_2 the second image, x_p, y_p are the pixel locations, x_0, y_0, z_0 are the vehicle position components, $\Delta x_0, \Delta y_0, \Delta z_0$ are changes in the vehicle/camera position components, and z is the scene depth, the only unknown in this equation.

The ranging equation can be further simplified by invoking the following assumptions:

- a) The image is assumed to consist of constant gradient patches.
- b) The image baseline is assumed to be fixed between images.

Under these assumptions, the Image-based ranging equation can be written in a more concise form as:

$$E_2 - E_1 = K \delta$$

Here, K is the quantity within the large square brackets, and δ is the inverse depth of the scene.

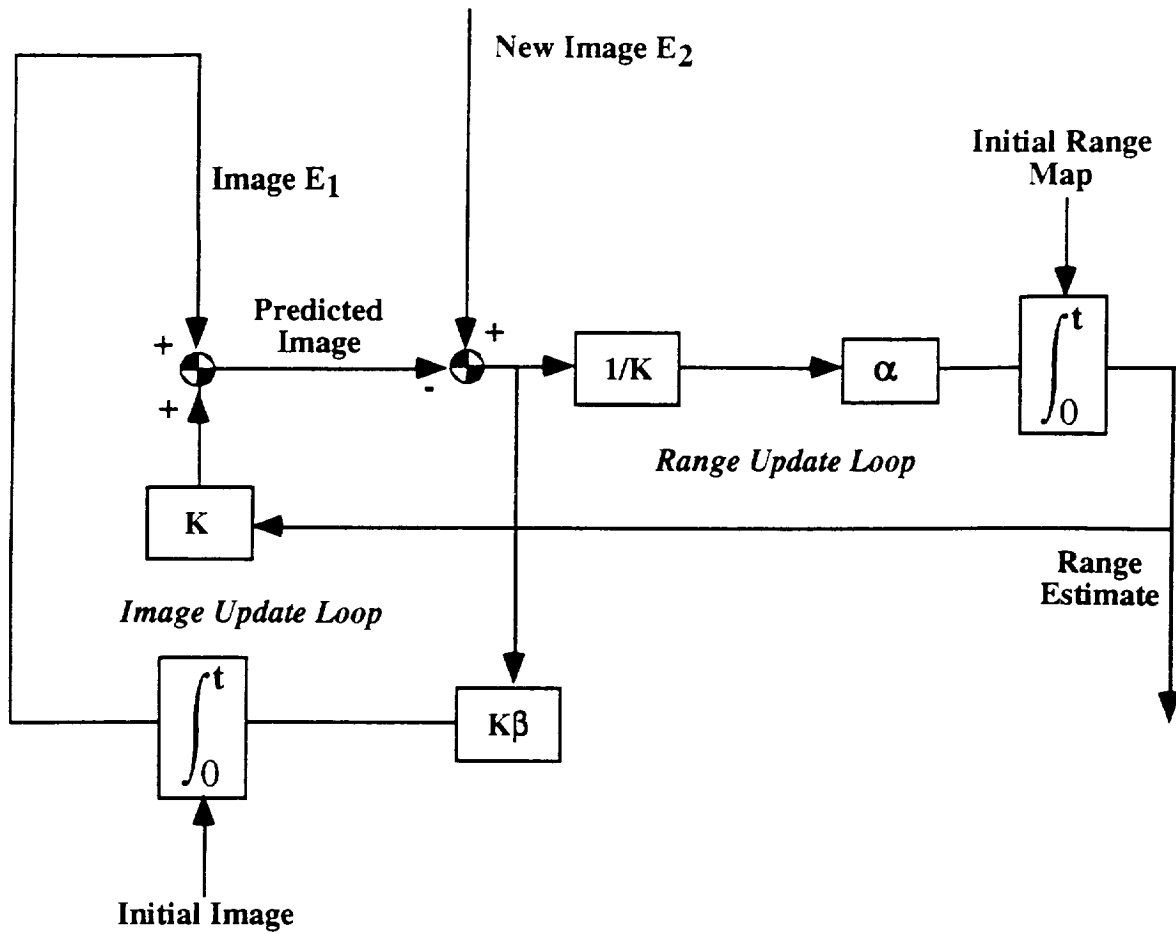


Fig. 4. Predictor-Corrector Scheme for Image-Based Ranging

This expression can be used to formulate the predictor-corrector technique. Various steps in this procedure are given in the following:

1. Image Prediction: Starting with the image E_1 , estimated scene depth $\hat{\delta}$, the predicted image $\hat{E}_2$ is

$$\hat{E}_2 = E_1 + K \hat{\delta}$$

2. Let the measured image E_2 . If we knew the exact scene depth δ , the measured image would have been: $E_2 = E_1 + K \delta$. The error in inverse of scene depth can be obtained by subtracting the predicted image from the actual as:

$$\hat{E}_2 - E_2 = K (\hat{\delta} - \delta) = K e$$

3. The scene depth error can then be computed as:

$$e = \frac{\hat{E}_2 - E_2}{K}$$

4. Correct the depth estimate using computed depth error:

$$\hat{\delta}_{i+1} = \hat{\delta}_i + \alpha e$$

5. Correct the original image using the error between predicted image and the measured image..

$$E_1 = E_1 + \beta K e$$

6. Return to step 1.

Fig. 4. gives a block diagram of the simplified predictor-corrector scheme. Note that if K is constant, the block diagram represents a linear, time-invariant system.

Using elementary block diagram manipulations, it is possible to show that the system will be stable. Specifically, it is possible to demonstrate the following:

1. Starting with an arbitrary initial guess of the inverse scene depth, it can be shown that the inverse depth estimates uniformly go to zero if the pixel intensity remains constant. (motion implies a non zero value of K). Note that this situation corresponds to an object located at infinity.
2. If the camera is moving towards the scene at a constant rate, since the scene patch has been assumed to have constant gradient, the measured irradiance will uniformly increase at any pixel other than the one at the center of the image. In this case, it can be shown that the predicted image irradiance and the actual image irradiance will closely track each other.

Conclusions

Initial research on combining geometry of scene with the corresponding image was given . Various tradeoffs involved in the synthesis of an image predictor was outlined. Linearized approaches to the problem were examined. The utility of the predictor in an image-based ranging scheme was illustrated.

Next Research phase will focus on the synthesis of a corrector algorithm. A synthetic vision algorithm using the predictor-corrector algorithm will also be demonstrated.

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